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Optical rotatory power of quartz between 77 K and 325 K for 1030 nm wavelength

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Abstract: We report on the experimental characterisation of the temperature dependence of the optical rotatory power of crystalline right-handed α-quartz at 1030 nm wavelength. The temperature range covered in this study is between 77 K and 325 K. For the measurement we propagated light through a 13.11 mm thick quartz plate collinearly with the optic axis. The plate is anti-reflection coated and rotates the polarisation plane of 1030 nm light by 89.3 deg at room temperature, corresponding to a specific rotatory power of 6.8 deg/mm. When placed between parallel polarisers, the transmission through the system was 0.03% at room temperature and increased to 1% at 77 K, showing a measurable change in rotatory power. At 77 K, the angle of rotation imparted by the quartz plate is 85 deg, corresponding to a specific rotatory power of 6.5 deg/mm. To the best of our knowledge, this is the first time that the temperature dependence of optical activity of α-quartz is reported for cryogenic temperatures in the infrared. We expect that the measurement results provided in this paper will assist in the design and characterisation of optical systems operating under cryogenic conditions.

1. Introduction

The temperature sensitivity of the properties of transparent materials is of considerable interest for the development of optical systems. Crystalline α-quartz material is widely used for polarisation optics because of its anisotropy and high optical transparency over a wide range of wavelengths, from near infrared to ultraviolet. Crystalline quartz is an ideal material for high power laser applications because it can be produced with high purity, required to avoid laser-induced damage and beam distortion. The trigonal crystalline structure of α-quartz results in positive birefringence, a property exploited for the realisation of waveplates. In addition to birefringence, the spiral molecular arrangement along the trigonal axis (optic axis) of quartz induces optical activity, resulting in the rotation of the polarisation plane of light propagating through the material. This property is used for the realisation of polarisation rotators, which find application, for example, in schemes for the compensation of stress-induced birefringence [1,2]. In order to optimise system design, information on the temperature dependence of optical activity in quartz is required. A number of published works report on the temperature dependence of optical activity of quartz above room temperature in the visible range [3–7]. However, an increasing number of high power lasers relies on cryogenic cooling to manage thermal loads and to increase system efficiency [8,9]. In particular, some thermally-induced stress birefringence compensation schemes benefit from the use of polarisation rotators at cryogenic temperatures [10]. As a result, interest in the

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optical properties of quartz at lower temperatures is rising; however, existing literature does not provide information on optical activity of quartz at low temperatures at the wavelengths commonly generated by high power lasers. Data at cryogenic temperatures has so far been provided only for visible radiation (wavelengths between 404.7 nm and 670.8 nm) by Molby, who measured it at 83 K and 300 K [11]. Subsequently, Chandrasekhar derived a formula to fit experimental data at room temperature for wavelengths between 150 nm and 3210 nm and at cryogenic temperatures for wavelengths between 400 nm and 670 nm [12]. In this paper, we report on the experimental characterisation of the dependence of optical activity of quartz for temperatures between 77 K and 325 K at 1030 nm wavelength, at which lasers based on Yb:YAG gain material operate [13]. The measurements were performed on a 13.11 mm thick quartz plate using 1030 nm light propagating collinearly with the optic axis. The measurements showed that at room temperature the quartz plate has a specific rotatory power of 6.8 deg/mm. At 77 K, this value decreases to 6.5 deg/mm. To the best of our knowledge, this is the first time that rotatory power of quartz is characterised in the infrared at cryogenic temperatures.

2. Materials and methods

2.1. Crystalline quartz material

Crystalline α-quartz belongs to the trigonal system, and therefore exhibits uniaxial birefringence. As a result of the helical arrangement of quartz molecules around the trigonal axis (optic axis), optical activity effects are observed in addition to birefringence. In purely optically active materials, circularly polarised light propagates unchanged, with left- and right- circular polarisations propagating at different speeds, determined by refractive indices n_L and n_R, respectively. It can be shown that this effect causes the polarisation plane of light to continuously rotate during propagation through the material. Propagation over a geometric path length L causes the polarisation plane to rotate by an angle [14]:

$$\gamma(T) = \frac{\pi}{\lambda}\Delta n(T)L(T), \tag{1}$$

where λ is the wavelength of light, T is the temperature of the material and where

$$\Delta n(T) = n_L(T) - n_R(T). \tag{2}$$

The specific rotatory power of the material is calculated as:

$$\rho(T) = \frac{\gamma(T)}{L(T)} = \frac{\pi}{\lambda}\Delta n(T). \tag{3}$$

The optical rotatory power of quartz is most easily observed when light propagates along the optic axis of the material. Furthermore, light propagating along the optic axis of quartz is not affected by birefringence, thus allowing the contribution of optical activity to be isolated. For this reason, measurements were performed on a z-cut right-handed crystalline quartz cylindrical plate (i.e. the input and output surfaces of the plate are cut perpendicularly to the optic axis), anti-reflection (AR) coated for 1030 nm wavelength. The sample (RT-10-1030-90, Melles Griot) has a diameter of 25.4 mm and a thickness of 13.11 mm. The rotation angle imparted at room temperature by the quartz plate across its aperture was measured using a polarimeter (StrainMatic, Ilis). The result, displayed in Fig. 1, shows that the root mean square rotation angle across the aperture for 1030 nm wavelength is 89.3 deg.

2.2. Experimental setup

The measurements of the rotatory power were carried out by means of an extinction method, using the experimental setup shown in Fig. 2. The figure also shows how the Cartesian reference system used throughout this paper is defined.

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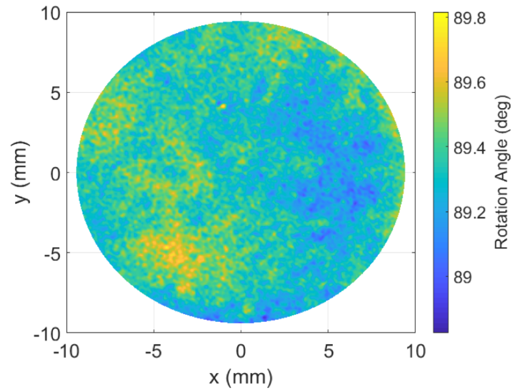

Fig. 1. Rotation angle imparted by the quartz plate across its aperture at room temperature and 1030 nm measured using a polarimeter.

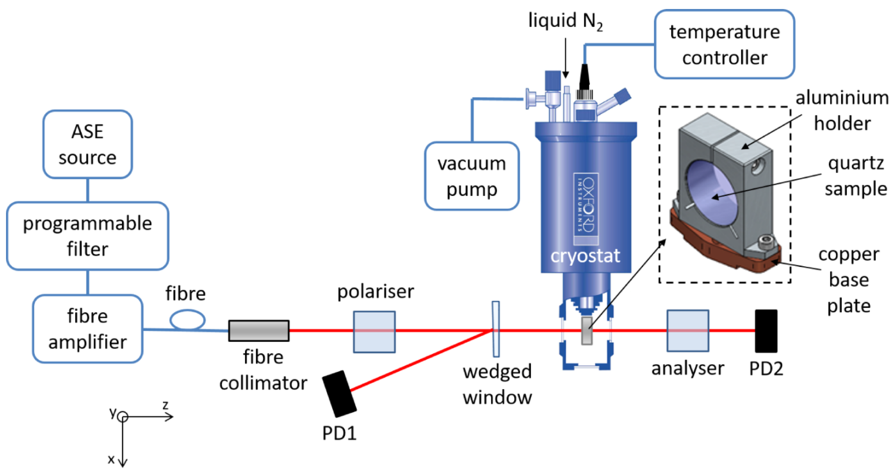

Fig. 2. Experimental setup used to characterise the temperature dependence of the rotatory power of quartz (PD1, PD2 = photo-detectors). The insert shows the holder in which the quartz sample is mounted.

Laser radiation is generated by an amplified spontaneous emission (ASE) source (BKTel). An external programmable optical filter (Waveshaper 1000S/1U, Finisar) filters the emission from the ASE source to select a 0.3 nm bandwidth spectrum centred around 1030 nm. A fibre amplifier (BKTel) amplifies the filtered radiation, which is subsequently collimated using a fibre collimator. A polarising beam splitter cube (CM1-PBS253, Thorlabs), further referred to as ”polariser”, selects the vertical polarisation component (i.e. electric field vector parallel to the y-axis of the Cartesian coordinate system). After the polariser, the beam has a power of 14 mW and is directed onto the quartz sample under study, which is located inside an optical cryostat (Optistat DN-V2, Oxford Instruments). The sample is mounted directly below the heat exchanger of the cryostat, using a copper base plate and an aluminium holder, which provides thermal contact over the whole outer surface of the sample (see the insert in Fig. 2). The temperature was measured using a platinum resistance thermometer attached to the copper plate. Fused silica windows, AR coated to reduce surface reflectivity below 0.5% for 1030 nm wavelength, allow optical access to the sample. The sample was orientated normal to the incident beam. The polarisation state of the beam transmitted through the sample was characterised using a polarising beam splitting cube

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(PBS103, Thorlabs), further referred to as "analyser", which can be rotated around the z-axis. A silicon photo-detector, indicated in Fig. 2 as PD1, monitors the power of the beam incident on the sample by continuously measuring the reflection off one surface of a wedged window. Another photo-detector, indicated as PD2, measures the power of the beam transmitted through the analyser. Both photo-detectors (PH100-Si-HA-OD2, Gentec-EO) were used with additional 1000 nm long-pass filters (FGL 1000M, Thorlabs) to suppress background light. Before the experiment, the power incident onto the quartz sample was calibrated by positioning PD2 directly behind the wedged window and by simultaneously measuring signals provided by PD1 and PD2. The calibrated signals were used to measure the transmission through the system as the ratio between the output power (after the analyser, as measured by PD2) and the power incident onto the quartz sample (after the wedged window).

3. Measurement results

Initially the analyser orientation was set to vertical, parallel to that of the polariser, as shown in Fig. 3(a). Without the quartz rotator in the beam path, the rotation angle of the analyser was adjusted so as to yield minimum rejected power. Transmission with the quartz rotator in place was measured at temperatures between 77 K and 325 K in steps of 5 K. After changing the temperature, the sample was given 10 min to thermalise before a measurement was taken. Experimental results are shown in Fig. 3(b).

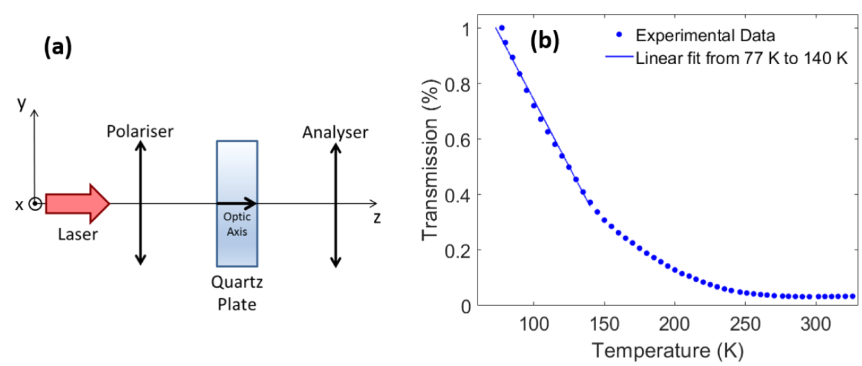

Fig. 3. Orientation of the transmission axes of the polariser and analyser and of the optic axis of the quartz plate with respect to the reference system (a). Dependence of transmission on the temperature of the quartz sample while the transmission axes of polariser and analyser are kept parallel to the y-axis (b). Data shown in this article are available at [15].

Results show that minimum transmission of 0.03% is achieved for temperatures above 270 K and transmission increases with decreasing temperature, reaching 1% at 77 K. This measurement confirmed the presence of a measurable variation of the optical rotatory power over the temperature range under consideration. This variation is influenced by a combination of material contraction due to the reduction in temperature and of a change in the refractive indices n_L and n_R. Data on the temperature dependence of the linear expansion coefficient of quartz in the direction parallel to the optic axis is reported in [16]. It is interesting to note that the derivative of the curve shown in Fig. 3(b) (i.e. the rate of change as a function of the temperature) changes around 140 K, as highlighted in Fig. 3(b) by the addition of a linear fit to the data points below 140 K. This effect, possibly due to structural changes of quartz at low temperatures [17,18], will be subject to further investigation. In order to determine how much the quartz plate rotates the polarisation over the temperature range under analysis, an additional set of measurements was performed. As the temperature of the quartz sample and the orientation of the transmission axis of the polariser were kept constant, the transmission axis of the analyser was rotated by an angle ϕ around the

z-axis, with $\phi = 0$ deg meaning that the axes of polariser and analyser are parallel. Minimum transmission at $\phi < 0$ deg means that the quartz plate rotates the polarisation by less than 90 deg, and $\phi > 0$ deg means that the polarisation is rotated by more than 90 deg. The measurement was repeated by varying the temperature between 77 K and 325 K in 25 K steps. At each temperature level, the orientation ϕ of the transmission axis of the analyser was varied in steps of 2 deg between -30 deg and +20 deg. The resulting experimental data are shown in Fig. 4(a) for a subset of temperatures. No substantial change was visible in this representation between 325 K and 200 K, and therefore only the former value is included in the graph. Figure 4(b) shows a zoomed-in view of the experimental data and fitting curves for ϕ values between -10 deg and 5 deg. Data points are fitted with fifth order polynomial fitting curves. From Fig. 4(b) it is possible to observe that, as the temperature is decreased, the minima of the fitting curves shift to lower ϕ values. Based on the definition of ϕ, this corresponds to a reduction in the rotation of the polarisation plane of light propagating through the sample.

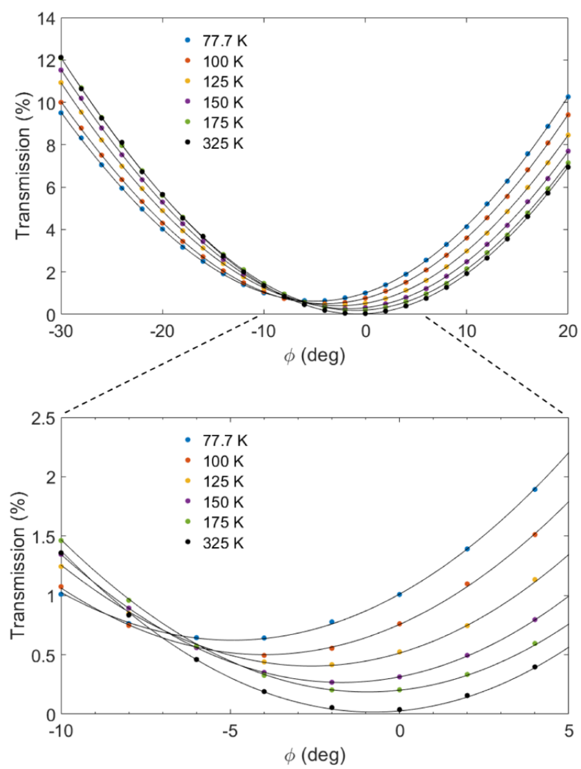

Fig. 4. Experimental data points (dots) and polynomial fitting curves (black lines) showing the temperature dependence of the transmission through the system as the axis of the analyser is rotated (a). Zoomed-in view of experimental data and fitting curves for ϕ values between -10 deg and 5 deg (b).

The angle ϕ_{min} for which minimum transmission is achieved was derived from the polynomial fits. From Fig. 4(b) it is possible to observe that, as temperature decreases, the transmission at ϕ_{min} increases, reaching 0.6% at 77 K. Figure 5 shows the dependence of transmission at ϕ_{min} as temperature is varied.

The rotation angle γ imparted by the quartz plate was calculated as 90 deg + ϕ_{min} and its dependence on temperature is shown in Fig. 6.

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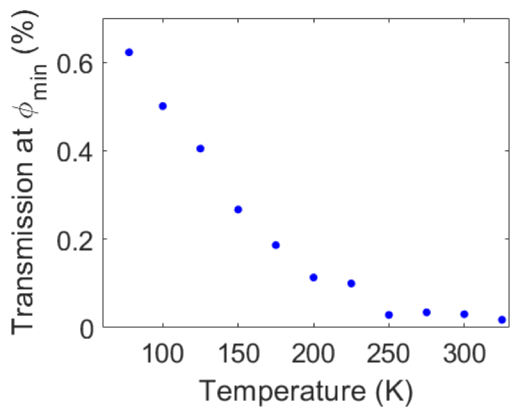

Fig. 5. Temperature dependence of the transmission at ϕ_{min}.

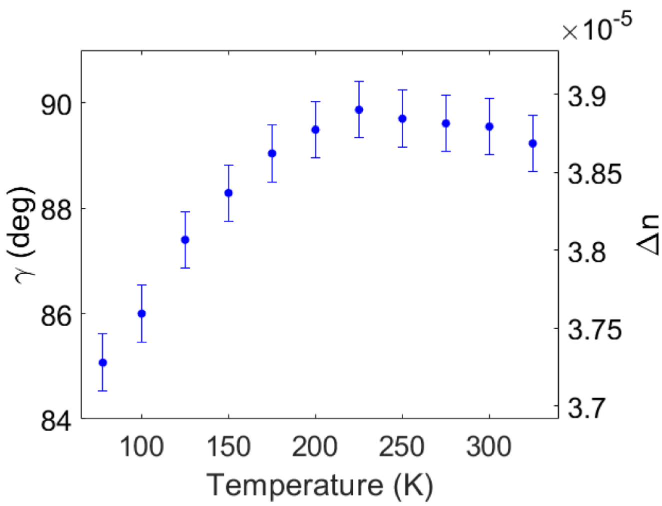

Fig. 6. Temperature dependence of the rotation angle γ imparted on the polarisation plane by the quartz plate and of the refractive index difference Δn.

At 77 K, the rotation angle is 85 deg which, based on Eq. 3, corresponds to a specific rotatory power of 6.5 deg/mm. As the temperature is increased above 250 K, the rotation angle increases to values around 89.5 deg, in agreement with the polarimeter measurement shown in Fig. 1. This value corresponds to a specific rotatory power of 6.8 deg/mm and it is in agreement with the value predicted in [12]. Error bars in Fig. 6 take into account uncertainty in laser power measurement (± 0.15%), sample length (± 0.001 mm), and angular orientation of the analyser (± 0.5 deg), which is the main source of error. The derivative of the curve shown in Fig. 6 (i.e. the rate of change of the rotation angle as a function of the temperature) changes around 200 K. As noticed earlier, this could be also due to structural changes occurring in quartz at low temperatures [17,18]. Further research will be required to validate this hypothesis. According to Eq. 1, a change in rotation can result from both a change in length L and in the difference between the refractive indices Δn. The linear expansion coefficient data for the direction parallel to the optic axis reported in [16] was used to calculate the length of the sample as a function of temperature. As shown in Fig. 7, over the temperature range under consideration, the length changed by 0.13%.

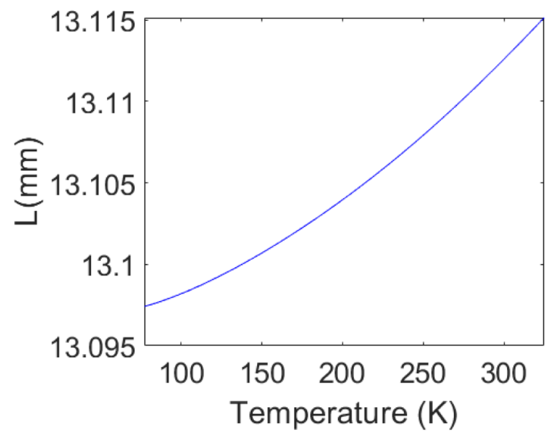

Fig. 7. Temperature dependence of the length of the quartz sample calculated using the linear expansion coefficient data reported in [16].

It follows therefore that the main contributing factor to the change in rotation angle with temperature is a change in the refractive index difference Δn, which was calculated using Eq. 1, the $L(T)$ values in Fig. 7 and $\gamma(T)$. Over the temperature range under consideration, the change in refractive index difference Δn is $2.1 \cdot 10^{-6}$.

4. Conclusion

In this paper, we measured the rotatory power of a right-handed crystalline α-quartz polarisation rotator at temperatures between 77 K and 325 K for 1030 nm light. To the best of our knowledge, this is the first time that optical activity of α-quartz has been characterised at cryogenic temperatures in the infrared. The measurements showed that at room temperature the quartz plate has a specific rotatory power of 6.8 deg/mm, while at 77 K this value reduces to 6.5 deg/mm. The experimental data show that the polarisation state of the beam transmitted through the quartz rotator is no longer purely linear, since the minimum transmission through the measurement system at 77 K rises to 0.6%. This could be the consequence of a small error in the cut of the quartz rotator plate or the introduction of mechanical stress due to differential thermal expansion between the sample and the holder. These effects would cause a small contribution from birefringence (and its own temperature dependence) to appear. Despite the reduction in optical rotatory power of quartz with temperature, we expect that quartz rotators optimised for room temperature will still perform sufficiently well down to 77 K for most applications. We also expect that this data will be useful for optimising quartz rotators for particular operating temperatures.

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Optical Materials EXPRESS

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